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Impacts of climate change on future water availability for hydropower and public water supply in Wales, UK

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A R T I C L E I N F O

Keywords:
Hydroelectric power
Hydroclimatic change
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Trend analysis
Water resource management
Water supply-demand balance

A B S T R A C T

Study region: Wales, United Kingdom.
Study focus: Climate change is predicted to have a large impact on the hydrological regimes of Welsh rivers. However, its influence on the abstraction capability of key sectors, such as public water supply (PWS) and hydroelectric power (HEP), is not yet fully understood. We use the Soil and Water Assessment Tool (SWAT) to generate future (2021–2079) streamflows under a worst-case scenario of greenhouse gas emissions (Representative Concentration Pathway 8.5) at two catchments in Wales, the Conwy and Tywi. SWAT streamflow output is used to estimate total unmet demand for PWS and changes in generation characteristics for HEP. PWS unmet demand is assessed using the Water Evaluation And Planning (WEAP) system under increasing, static, and declining demand scenarios. Mann-Kendall analysis is performed to detect and characterise trends.
New hydrological insights for the region: Under all future demand scenarios, there is increased occurrence of insufficient streamflow to satisfy PWS demand. For HEP, decrease in annual abstraction volume results in a loss of generation potential, despite an increasing number of days that maximum abstraction is reached. Changes in HEP generation and PWS availability are most pronounced in the medium-term (2021–2054), with rate of change slowing after 2060. We provide a novel perspective on future water resource availability in Wales, giving context to management planning to ensure future PWS sustainability and HEP generation efficiency.

1. Introduction

Climate change is a key driver of hydrological regime alteration globally, with prevailing weather conditions being inextricably linked with streamflow. Given the dependence of society on river systems for everyday life, it is of great importance to understand how climate change will impact water resource availability. In the UK, it is widely accepted that climate change will lead to hotter, drier summers and warmer, wetter winters, as well as an increase in the magnitude, frequency and duration of extreme weather events (ASC, 2016a; Lowe et al., 2018). In terms of streamflow, an exacerbation of low and high flows is expected, as well as a reduction in average summer and autumn flows and an increase in winter and spring average flows; these opposing trends should leave annual averages relatively stable (Christierson et al., 2012; Kay et al., 2020; Prudhomme et al., 2012; Watts et al., 2015). Climate change and streamflow responses in Wales specifically are projected to be in line with the trends suggested for the rest of the UK, with summer mean and maximum temperatures, as well as winter total and extreme precipitation volumes, predicted to increase (ASC, 2016b; Kay

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et al., 2020). These changes have the potential to cause a large impact on major water consuming sectors such as agriculture, heavy industries, public water supply (PWS), and hydroelectric power (HEP) generation. The Adaptation Sub-Committee (ASC) of the Committee on Climate Change, for example, suggests that PWS and agricultural water demand for irrigation could be two of the most pressurised sectors in the UK under future climate and streamflow changes, with demand potentially outstripping available water resources (ASC, 2016a). Furthermore, Arnell and Delaney (2006) detailed how, even at that time of publication, PWS companies in England and Wales would need to adapt to ensure sufficient raw water resources due to changes to low flow regimes. In Wales, Carless and Whitehead (2013) demonstrate decreasing summer and autumn streamflows with corresponding increases in winter and spring. In the given context of a theoretical 99 kW micro-HEP installation, this causes an accentuation of seasonality in terms of energy generation, with extra supply in wetter seasons compensating for lower supply in drier seasons, leading to an annually stable situation (Carless and Whitehead, 2013). However, these changes are likely to be catchment-specific, depending on the individual catchment's topographic and land cover characteristics as well as the prevailing weather patterns.

In 2018, renewable energy accounted for 25 % of the total electricity generated in Wales, with HEP making up 5.2 % of this, and therefore 1.3 % of overall Welsh electricity generation (Welsh Government, 2019). A large increase in the number of small-scale HEP schemes has occurred in the last eight years due to financial incentives in the form of Feed-in-Tariffs (FiT) (Welsh Government, 2019), and also given that most opportunities for large-scale schemes have been exhausted (Carless and Whitehead, 2013). However, due to the curtailment of the FiT scheme in 2019, the number of new developments has slowed, with further schemes only likely to be commissioned where conditions are optimal (Welsh Government, 2019). These types of schemes, usually run-of-river in design, generally have little or no water impoundment, making them particularly vulnerable to changes in hydrological conditions. Run-of-river HEP schemes are usually designed and optimised on the basis of historical flow, with flow duration curves used to set abstraction conditions. While this method is a good starting point for designing the most efficient system to maximise power output, it neglects to account for future streamflows. Climate change has the potential to cause major alteration to the hydrological characteristics of river systems, modifying the timing and quantity of available water. High and low flows are particularly likely to be affected (ASC, 2016b; Kay et al., 2020; Sayers et al., 2015; Watts et al., 2015), and these extreme flows are often important in terms of HEP scheme design. In 2017, the Welsh Government set a target for 70 % of electricity consumed in Wales to be generated by renewables by 2030 (Welsh Government, 2019). HEP plays a small but important role in reaching this target, especially in the winter and spring seasons when electricity generation from other sources, such as solar PV, is lower. Therefore, understanding the nature of change in the

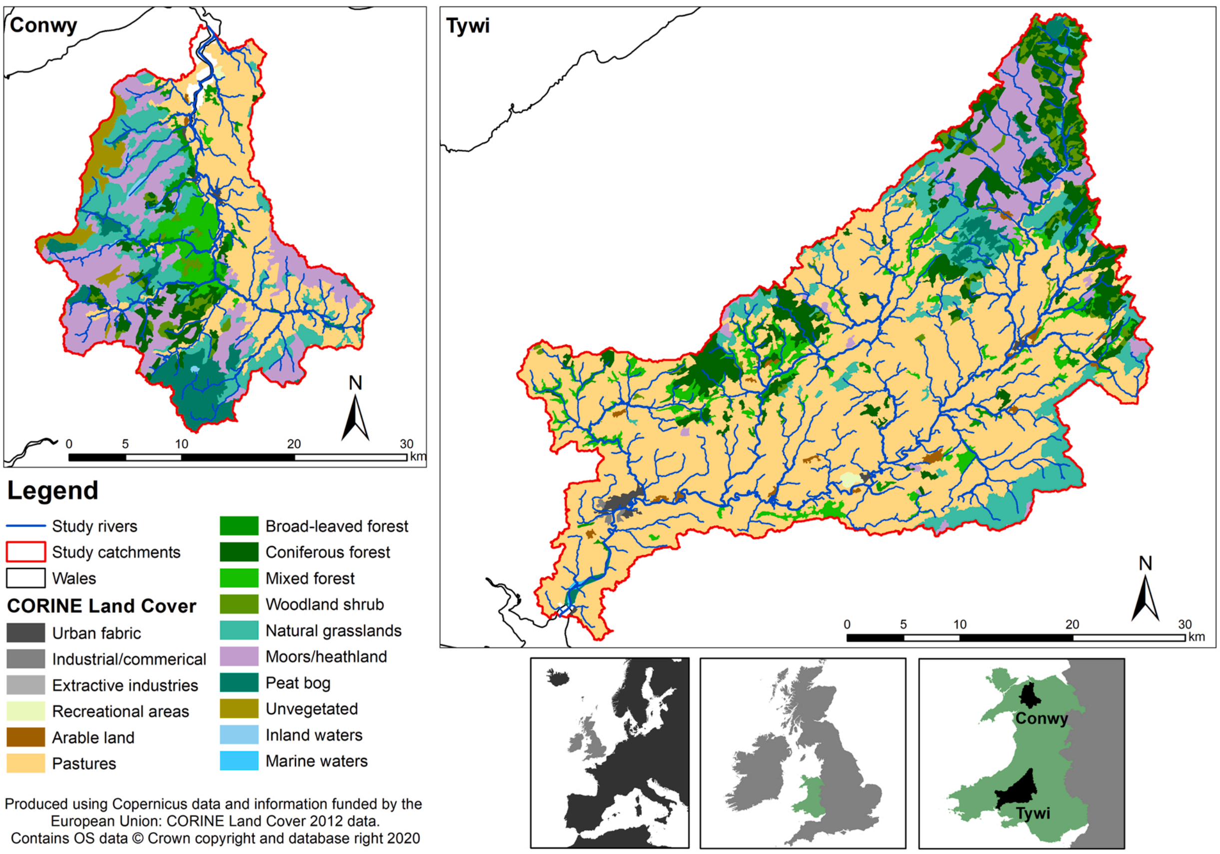

Fig. 1. Study catchments, displaying CORINE Land Cover classification (EEA, 2012). Inset, location of catchments within Wales, Wales within the UK, and the UK within Europe.

abstractable flow for HEP schemes under future climate change is crucial. This will allow for more robust planning of the future energy mix in Wales as well as maximisation of resource use efficiency and electricity generation.

PWS also relies heavily on surface waters in Wales, with over 95 % of the supplied water originating from rivers and lakes (DCWW, 2019a). In Wales, PWS is largely under the authority of Dŵr Cymru Welsh Water (DCWW), who provide an average of 800 million litres of water per day to over three million people (DCWW, 2019b). While the majority of surface water used is from lakes and reservoirs, a substantial proportion is taken from lowland river abstractions, especially for rivers in south Wales, such as the Wye, Usk and Tywi, which are often supported by upstream reservoirs in times of very low flow (DCWW, 2019b). While the water supply system in Wales is largely resilient to climate change, due to the amount of water stored, changes in climate still do have the ability to change the required water management and places greater pressure on the system (ASC, 2016b). The ASC report a 12 % supply-demand surplus for PWS in Wales, however, this is set to decline under projected population growth and climate change, with three of DCWW's water resource zones expected to be in deficit by the 2080s (ASC, 2016b; DCWW, 2019a).

Projected increases in the occurrence of low flows will impact how often PWS and HEP operators are permitted to abstract water from rivers in the future, with stringent hands-off-flow (HoF) regulations applied to abstractions to ensure the protection of low flows downstream. In addition, a greater occurrence of large flow events will potentially be of little use to abstractors to compensate for less abstraction potential due to low flows, if system capabilities, such as turbine size for HEP, do not allow for it. It is therefore important to study these future changes now, to successfully plan for systems that are resilient to climate change and make the most of available future flows.

In this paper, we study the impact of climate change on two catchments in Wales, the Conwy and Tywi, especially in terms of future water availability for small-scale HEP generation and PWS. This is a less-studied region of the UK in this regard, due to the perceived abundance of water resources in Wales. However, owing to both the reliance on surface waters for PWS and the large recent increase in small-scale HEP projects, this is an important area in which to understand future water resource changes.

2. Data and methods

2.1. Study catchments

Our two study catchments, Conwy and Tywi (Fig. 1), were selected due to their contrasting physical characteristics, especially in terms of catchment land use/land cover (LULC), mean catchment slope, and catchment area (Table 1); all potentially giving rise to differences in hydrological regime. These catchments are also exploited for their water resources in the form of HEP and PWS, with Natural Resources Wales (NRW) providing abstraction licenses for non-impoundment run-of-river HEP schemes in both the Conwy and Tywi (NRW, 2019). Both catchments are also used for PWS, however, only the Tywi catchment has an abstraction taken directly from the river, with PWS in Conwy sourced from reservoirs only (DCWW, 2019b). The downstream river-based abstraction in Tywi is supported in times of low flow by upstream releases from the Llyn Brianne reservoir (DCWW, 2019a). This abstraction supplies the largest drinking water treatment plant in DCWW's network, serving a population of ~400,000 in Swansea, Neath, Bridgend and the Vale of Glamorgan (DCWW, 2019b), making the abstraction an important location to study in terms of future water supply-demand balance.

The Conwy catchment is more mountainous in topography, with a steeper mean slope, and greater maximum elevation, peaking

Table 1
Key study catchments details. Catchment area, elevation, and slope data derived from 5 m resolution OS Terrain 5 DEM from Ordnance Survey; land use/land cover (LULC) data derived from 2012 CORINE Land Cover data (EEA, 2012). LULC categories and values shown in bold denote primary LULC classifications, subsequent non-bold entries show any further breakdown of the primary LULC classification into sub-categories.

		Conwy	Tywi
Catchment area (km^2)		541.8	1364.6
Maximum catchment elevation (m)		1062	801
Mean catchment slope (%)		19.7	16.6
Catchment land use/land cover (%)	**Urban**	**0.7**	**0.7**
	Agriculture	**30.6**	**64.6**
	Arable	0.1	0.7
	Pasture	30.5	63.9
	Forest	**13.7**	**16.0**
	Broadleaf	2.7	1.0
	Coniferous	5.5	10.1
	Mixed	5.5	4.9
	Scrub	**42.1**	**17.1**
	Natural grassland	16.6	8.4
	Moors and heathland	23.6	6.5
	Transitional woodland scrub	1.9	2.2
	Peat bog	**8.4**	**1.3**
	Sparsely vegetated areas	**4.1**	**0.0**

261 m higher than the Tywi, at 1062 m, near the summit of Snowdon. The Tywi catchment, however, has more than double the drainage area of Conwy, at 1365 km^2 to Conwy's 542 km^2 (Table 1). The catchments are also contrasting in terms of LULC (Fig. 1), with the Tywi being dominated by agriculture, pasture specifically (63.9 %), which is well-distributed throughout all but the highest elevations in the catchment. The Conwy catchment, on the other hand, has a larger proportion of scrubland (42.1 %), in particular moors/heathland (23.6 %) and natural grassland (16.6 %), mostly to the west of the main channel, with the eastern side being more pasture-dominated (Fig. 1). The Conwy also features a large peat bog in the south of the catchment, accounting for 8.4 % of total catchment LULC; this is significantly more than is seen in the Tywi (Table 1). Forests cover a slightly larger area of the Tywi (16.0 %) than the Conwy (13.7 %), but the mix of forestry types is different, with notably more coniferous forest in the Tywi (10.1 %), while the Conwy has equal proportions of coniferous and mixed forest (5.5 %; Table 1).

2.2. Future streamflow and climate projections

Future streamflows for both catchments were modelled at a daily resolution for the hydrological years 2021–2079, using the physically based, semi-distributed, continuous time-step, Soil and Water Assessment Tool (SWAT) hydrological model (Arnold et al., 2012, 1998; Neitsch et al., 2011). SWAT has been used extensively in the context of future hydrological regime change and water resources assessment globally (Coffey et al., 2016; Khan et al., 2020; Perra et al., 2018; Sultana and Choi, 2018; Yuan et al., 2019), with publications focussing on both HEP (Abera et al., 2018; Haguma et al., 2017; Park and Kim, 2014; Shrestha et al., 2016) and water availability (Bessa Santos et al., 2019; Rivas-Tabares et al., 2019; Sharma et al., 2016; Veettil and Mishra, 2016).

Initial input data for SWAT were obtained from Ordnance Survey (5 m resolution OS Terrain 5 DEM; Ordnance Survey, 2020), the EU soil database (version 2.0, specifically the Soil Geographical Database of Eurasia, a 1:1,000,000 scale vector dataset; European Commission, 2004) and the CORINE Land Cover dataset (Copernicus Land Monitoring Data; EEA, 2012). The OS Terrain 5 DEM is a high-resolution raster dataset, with a 5-metre post spacing (Ordnance Survey, 2017), and was chosen in order to provide the most accurate catchment delineation and water routing possible, as well as to maintain computational efficiency for the size of catchments studied. In terms of LULC, the CORINE dataset was chosen due to the close match of LULC categories between it and the pre-exiting SWAT LULC categories, allowing for easy input to, and interpretation by, the model. The CORINE dataset is accurate spatially to within 25 m, with a minimum mapping unit of 25 ha for areal features and width of 100 m for linear features; the accuracy of identified LULC type is greater than 85 % (EEA, 2017). The calculation of SWAT soil parameters was completed using the Pedo Transfer Function developed by Saxton and Rawls (2006), based on the characteristics associated with the given World Reference Base for Soil Resources (FAO, 1998) classification of each soil type.

Additionally, historical daily weather data (air temperature and precipitation) and streamflow data, both used for model calibration and validation, was sourced from the Centre for Ecology and Hydrology's (CEH) Climate, Hydrology and Ecology research Support System (CHESS) dataset (Robinson et al., 2017) and the National River Flow Archive dataset (NRFA, 2020), respectively. The gridded CHESS dataset was chosen due to its complete coverage across the catchments, especially when compared to data from individual meteorological stations, of which there are few with long, complete, and consistent records for the area. CHESS precipitation data is based on the CEH 1 km Gridded Estimates of Areal Rainfall (GEAR) dataset, which is an interpolated dataset based on meteorological station rainfall observations adjusted for topography, to provide full UK coverage (Keller et al., 2015). Temperature data for CHESS is downscaled to a 1 km grid, also taking account of topographical data, from the 0.5 degree gridded Climate Research Unit Time Series, version 3.21 dataset (CRU TS3.21), which is also based on meteorological station observations (Harris et al., 2014). In order to provide a single dataset of each climatic variable for each catchment, the mean value of all grid cells contained with a catchment was calculated for each day of the study period; it is this value, after inspection for anomalies, that has been used. Streamflow data was taken from gauges with as close to natural flow as possible, station 66011 for Conwy, and 60006 for Tywi.

Table 2
SWAT parameters calibrated through SWAT-CUP using the particle swarm optimisation method.

Parameter	Description	Input file location
ESCO	Soil evaporation compensation factor	.bsn
EPCO	Plant uptake compensation factor	.bsn
SURLAG	Surface runoff lag time	.bsn
GW_Delay	Groundwater delay	.gw
Alpha_BF	Baseflow alpha factor	.gw
GWQMIN	Threshold depth of water in shallow aquifer for return flow to occur	.gw
RCHRG_DP	Deep aquifer percolation fraction	.gw
REVAPMN	Threshold depth of water in shallow aquifer for "revap" to occur	.gw
GW_REVAP	Groundwater "revap" coefficient	.gw
ALPHA_BF_D	Baseflow alpha factor for deep aquifer	.gw
CANMX	Maximum canopy storage	.hru
CN2	SCS runoff curve number for moisture condition 2	.mgt
CH_N2	Manning's "n" value for the main channel	.rte
CH_K2	Effective hydraulic conductivity in main channel alluvium	.rte
SOL_AWC	Available water capacity of the soil layer	.sol
SOL_K	Saturated hydraulic conductivity	.sol
SOL_Z	Depth from soil surface to bottom of layer	.sol

The catchments were calibrated individually with the historical streamflow data, for a 14-year period of 1985–1998, following a 3-year model warm-up period. We used the Particle Swarm Optimisation (PSO) method (Kennedy and Eberhart, 1995) for model calibration through the SWAT Calibration and Uncertainty Programme (SWAT-CUP), with the Kling-Gupta efficiency (KGE) as the goodness-of-fit metric (Gupta et al., 2009). PSO is a complex but highly efficient method of calibration, capitalising on swarm intelligence to iteratively improve the model performance by finding the optimal parameter values within a given range (search space), taking inspiration from flocking birds (Kennedy and Eberhart, 1995). In practice, this entails a swarm of particles being initialised, with each particle in the swarm randomly assigned a position and velocity, the initial locations are evaluated for model fit, and these automatically become each particles' current best solution. The group's best solution is set at the value of the particle with the best fit of all particles. The individual particles then iteratively work towards, with a random function, a combination of their own and the groups best known position (Qi et al., 2015). The process stops once either a given KGE value is reached, or the number of swarm iterations is reached, whichever is sooner. This method of calibration was chosen due to the simultaneous multiple parameter calibration required, which can be accomplished by PSO, as well as its computational efficiency, which was important due to the number of parameters and size of the catchments studied. A total of 17 parameters (Table 2) were calibrated simultaneously, these were selected based on a literature review of studies operating in similar catchment types.

The calibration KGE values after 10 iterations with 10 particles (100 model runs per catchment) were deemed acceptable at 0.770 for Conwy and 0.841 for Tywi; a comparison of the observed and simulated streamflow for the calibration period is shown in Fig. 2. Following implementation of the calibrated parameters values into SWAT, we validated the model for the 1999–2014 period (once again with a 3-year model warm-up) and obtained the KGE values of 0.718 for Conwy and 0.717 for Tywi.

Future streamflows were projected based on the weather input derived from the UK Climate Projections 2018 dataset, 'Regional Projections on a 12 km grid over the UK for 1980–2080' (MOHC, 2018), the most recent projections available for the UK. These projections allow for the use of an ensemble of twelve regional climate models downscaled from the 60 km HadGEM3-GC3.05 global coupled model; for more information on these projections we direct the reader to Murphy et al. (2018). This projected future climate input is based on a worst-case scenario of future global greenhouse gas (GHG) emissions, in the form of Representative Concentration Pathway 8.5 (RCP8.5) from the Intergovernmental Panel on Climate Change (IPCC). RCP8.5 represents one of the worst emissions outcomes of a no-policy scenario, with high population growth, continued coal use, and no downturn in global GHG emissions (Riahi

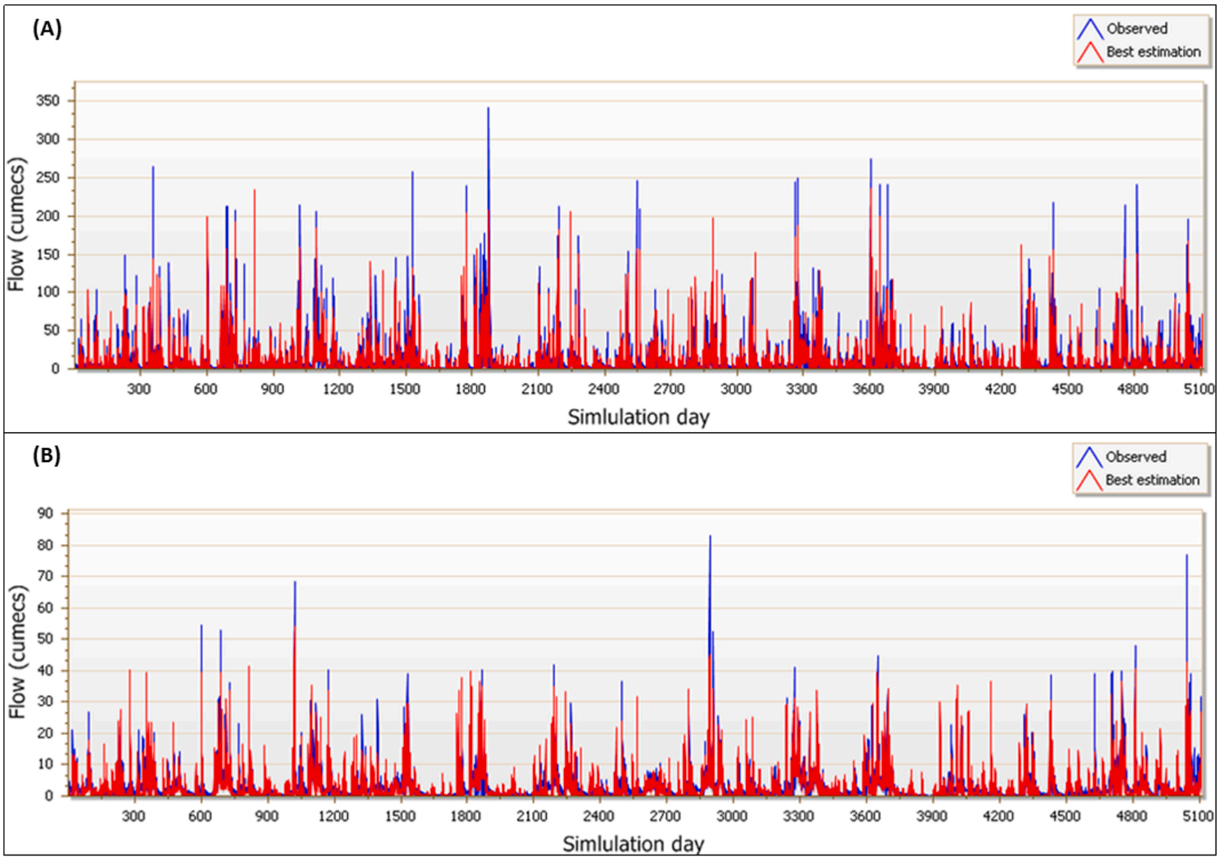

Fig. 2. Observed streamflow (blue) compared to the best simulation (red) for (A) the Conwy catchment, and (B) the Tywi catchment, following calibration for the period 1 st January 1985 to 31 st December 1998 (for interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

et al., 2011; van Vuuren et al., 2011), leading to a scenario of radiative forcing still rising by 2100, and not peaking until the 2200s (Moss et al., 2010; van Vuuren et al., 2011). This is an extreme future scenario, in the 90th percentile of future modelled outcomes of no climate change mitigation (van Vuuren et al., 2011) and has been used in this research despite the higher levels of uncertainty associated with it, due to the critical nature of the study subject, in particular PWS. To ensure an uninterrupted future PWS it is vital to take account of such a scenario, to allow for robust planning. In addition, in a future society where renewable energy is likely to make up a larger part of the overall energy mix, understanding the potential fluctuation in HEP generation caused by alteration in streamflows under climate change is highly important. A summary of future temperature, precipitation and streamflow is shown in

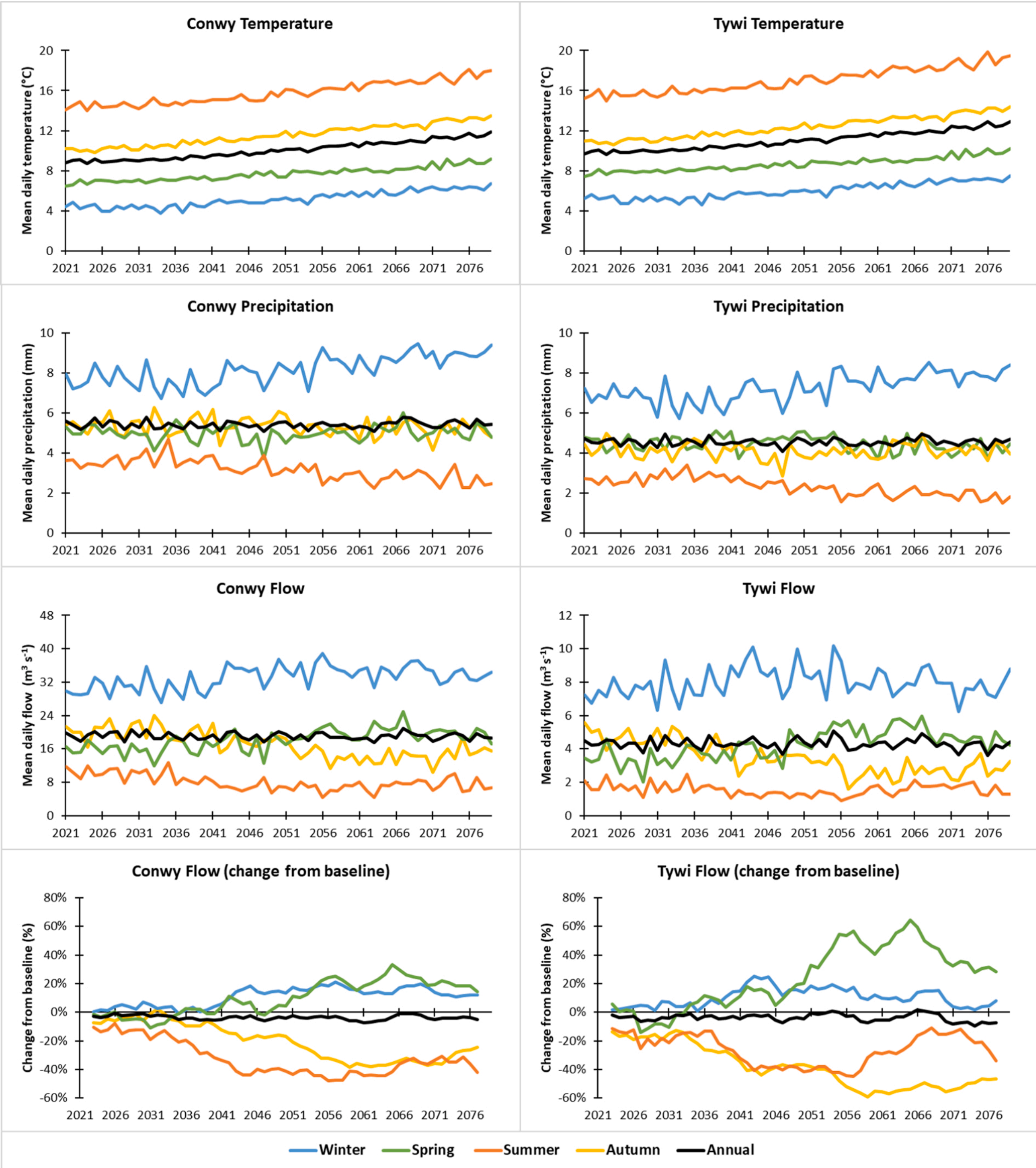

Fig. 3. Projections for seasonal and annual mean temperature, precipitation and streamflow for Conwy (left) and Tywi (right). Bottom panels shows percentage change from 1990-2010 baseline average for a 5-year moving average of seasonal and annual mean streamflow, at the gauging station locations identified in Fig. 4.

Fig. 3, the data shown for all three factors is based on the average of all twelve downscaled regional climate model ensemble members. Temperatures are projected to increase in all seasons, while precipitation and streamflow both increase in the winter and spring, but decrease in the summer and autumn, leading to a small overall annual reduction.

2.3. Hydroelectric power assessment

Assessment of changes in the abstraction regime for HEP locations was undertaken for non-impoundment, run-of-river based schemes only, of which there are a total of sixteen in Conwy, and nine in Tywi. Abstraction locations were obtained from NRW. Due to lack of specific information pertaining to each HEP scheme, such as abstraction licence conditions, scheme layout, generation capacity etc., abstraction conditions were based on general licensing guidelines laid out by NRW (NRW, 2020). Guidance from the organisation states that for schemes creating a depleted reach (i.e. run-of-river schemes) and that do not operate on rivers supporting salmon spawning or protected species, there are two types of abstraction permitted, Zone 2 (Z2) and Zone 3 (Z3) (NRW, 2020). It was assumed for the purposes of this study that all schemes operate under Z2 or Z3; a summary of the conditions placed on abstraction rates of these zones is made in Table 3. Schemes are categorised into either zone based on the gradient of the depleted reach, with those below 10 % gradient being Z2, and those above being Z3. As information on the actual depleted reach was not available, the average slope of the sub-basin immediately downstream of the abstraction location was taken, and the corresponding zone type applied (Fig. 4). Under the assumption that each HEP site abstracts the maximum amount of flow available to it, and given daily average streamflow (Q), Eqs. 1 and 2 were used to calculate daily average abstraction volume (A_{daily}) at each location in line with abstraction rates dependent on the site zone:

$$Q_{surplus} = Q - HoF \tag{1}$$

where HoF represents the compensation hands-off-flow release required to protect low flows and $Q_{surplus}$ is the amount of water available for abstraction, used to calculate A_{daily}:

$$A_{daily} = Q_{surplus} \times Q_{take} \begin{cases} 0, & if\ A_{daily} < A_{start} \\ A_{max,} & if\ A_{daily} > A_{max} \\ A_{daily,} & if\ A_{start} < A_{daily} > A_{max} \end{cases} \tag{2}$$

where Q_{take} is the proportion of flow available for abstraction as per the zone conditions, A_{start} refers to the minimum abstraction volume required to start, and for efficient operation of, the turbine, and A_{max} represents the maximum permitted abstraction volume. A further assumption was that an impulse turbine is in use at each site, as is common with small-scale HEP schemes in upper catchment reaches, such as those analysed in this study (Cobb and Sharp, 2013; Lilienthal et al., 2004; Židonis et al., 2015). Impulse turbines have largely high and stable efficiency after approximately 10 % of designed flow is achieved (Chitrakar et al., 2020; Novara and McNabola, 2018; Paish, 2002), making them ideal for settings with variable A_{daily} (Cobb and Sharp, 2013). For this reason, A_{start} was set at 10 % of A_{max} for each scheme, which is the assumed design flow volume.

2.4. Public water supply assessment

An assessment of the impact of future hydrological regime change on PWS was undertaken in the Tywi catchment only, due to the lack of river-based PWS abstraction in the Conwy catchment. The supply-demand balance at the aforementioned single major abstraction location (Fig. 4) was calculated using the Water Evaluation And Planning (WEAP) system (Raskin et al., 1992; Yates et al., 2005). WEAP is an integrated water resource management model that assimilates the demand and infrastructure management with physical hydrological processes and allows for multiple scenario analysis and comparison (Raskin et al., 1992; Yates et al., 2005). The WEAP model has been used extensively for scenario analysis related to water resource planning and allocation in a variety of contexts, such as the impacts of climate and land use change (Ashofteh et al., 2013; Esteve et al., 2015; Joyce et al., 2011; Purkey et al., 2008; Tena et al., 2019), reservoir and dam operation planning (Azari et al., 2018; Demertzi et al., 2014; McCartney and Menker Girma, 2012; Vonk et al., 2014), ecosystem requirements and environmental protection (Thompson et al., 2012; Fatemi et al., 2013; Flores-López et al., 2016; Momblanch et al., 2020), and population increase and urbanisation impacts (Alamanos et al., 2020; Höllermann et al., 2010; Kumar et al., 2017; Toure et al., 2017). However, WEAP is not designed for detailed optimisation studies, such as that required for HEP (Yates et al., 2005). For this reason, the model has only been used in the PWS analysis for this study.

Table 3
Abstraction conditions as defined by NRW guidelines for Zone 2 and Zone 3 sites (NRW, 2020).

Condition	Definition	Zone 2	Zone 3
Depleted reach gradient	Gradient of the stream between abstraction point and return flow	<10 %	>10 %
Hands-off-flow (HoF)	Streamflow rate below which abstraction is not permitted	Q_{95} [a]	Q_{95} [a]
Maximum abstraction volume (A_{max})	Maximum rate of abstraction, above which no additional flow can be taken	1.3 x Q_{mean} [b]	Q_{mean} [b]
Percentage take (Q_{take})	Proportion of flow between HoF and A_{max} permitted for abstraction	50 %	70 %

[a] Streamflow volume exceeded 95 % of the time.
[b] Mean annual streamflow volume.

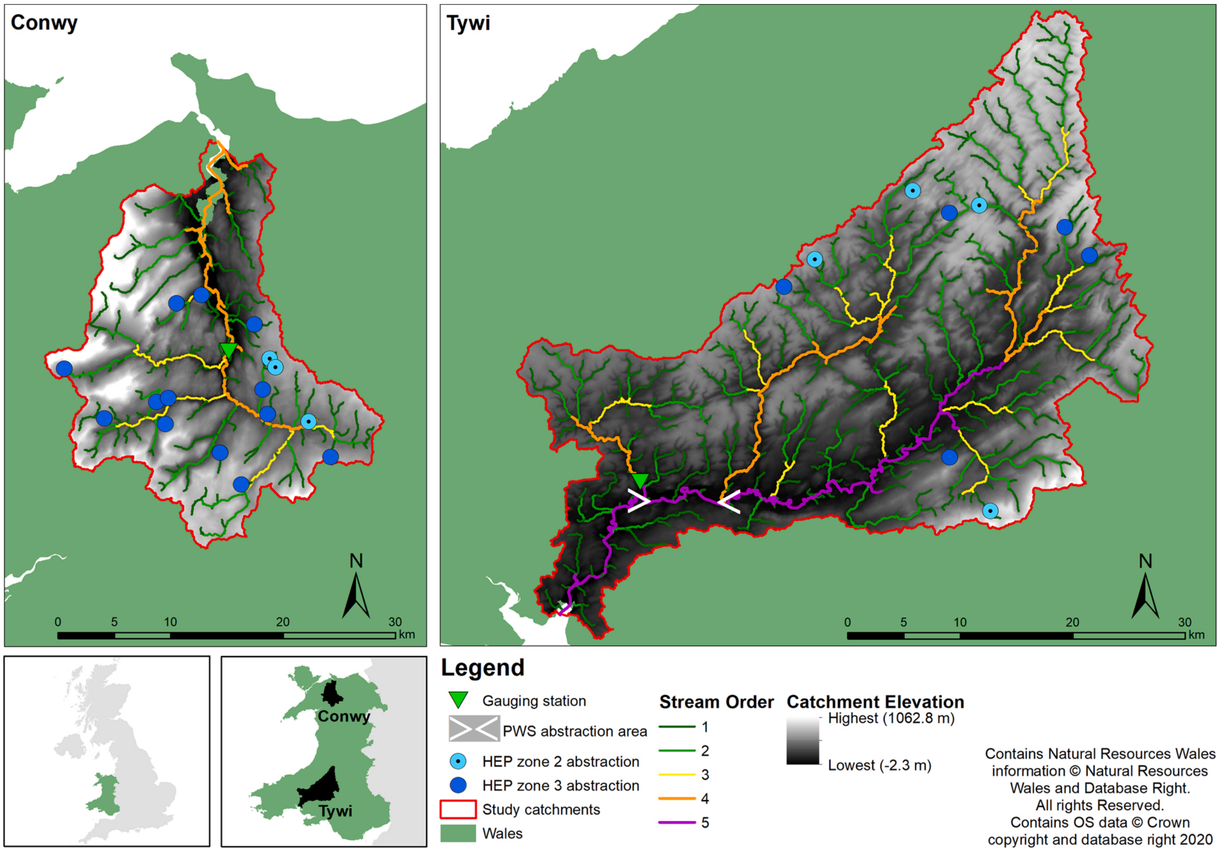

Fig. 4. Studied abstraction locations for hydroelectric power (HEP) and public water supply (PWS); HEP locations categorised by abstraction regime type. The '>' and '<' markers denote the river section of the PWS abstraction, as to identify the specific location would violate data licence conditions. River network, with stream orders defined by Strahler method, and catchment elevation, based on 5 m resolution OS Terrain 5 DEM from Ordnance Survey, also shown.

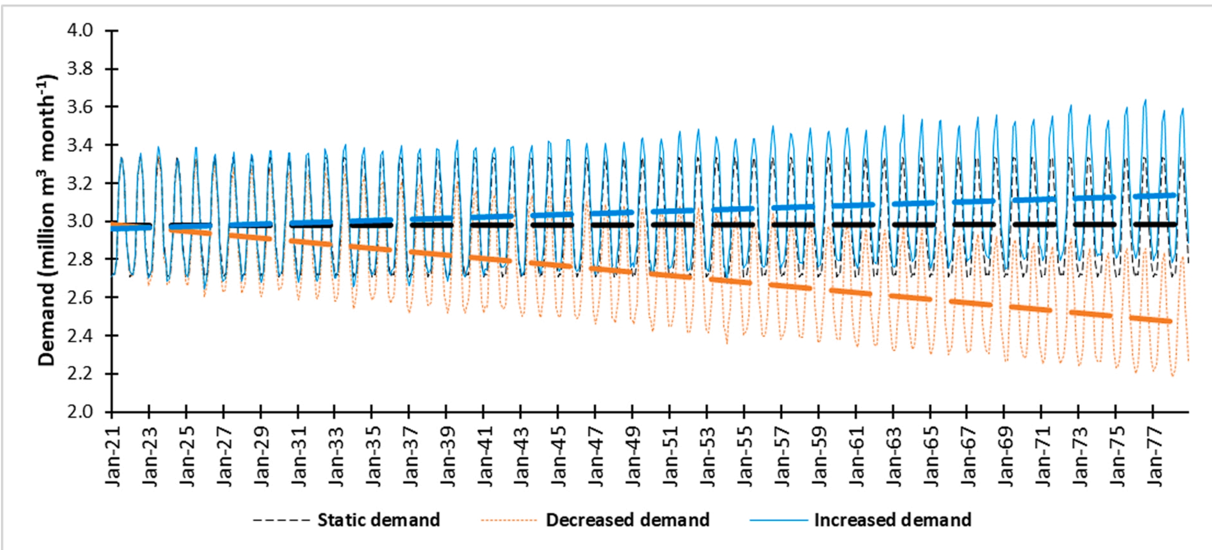

Fig. 5. Future monthly total water demand at the Tywi public water supply abstraction under the three future water demand scenarios: increased, static and decreased. Thick dashed lines represent the linear trend of each scenario.

Future total daily water demand was calculated for three scenarios (Fig. 5), representing increased, static and declining abstraction requirement. The increased demand scenario was based on the linear relationship between historical daily temperature and total water abstraction from the location, as presented by Dallison et al. (2020). The water abstraction data was provided by DCWW for January

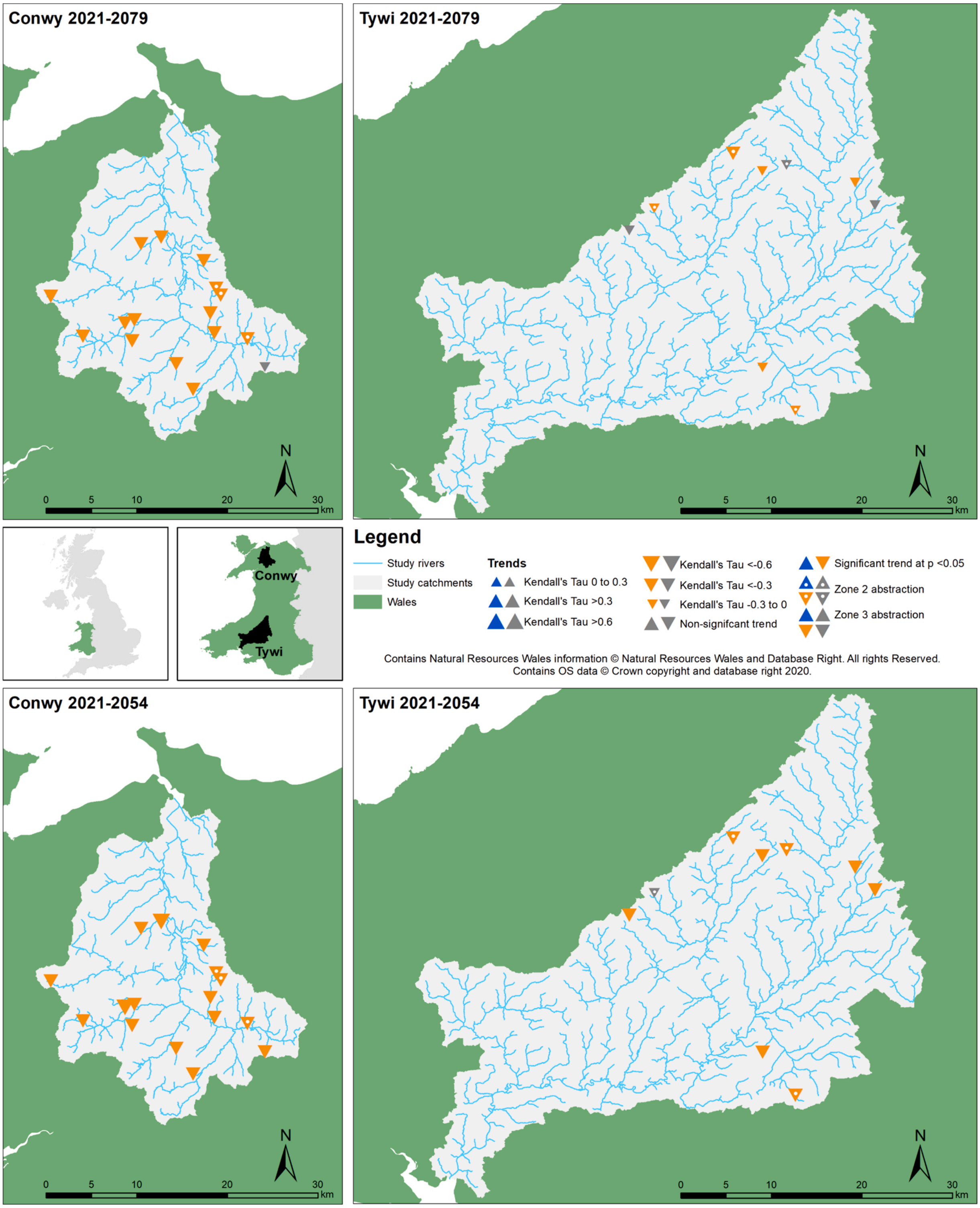

Fig. 6. Overview of the direction, magnitude and significance of annual trends in number of days A_{start} achieved for the periods 2021-2079 (top) and 2021-2054 (bottom). Trends detected by Mann-Kendall trend analysis for individual hydroelectric power abstraction locations.

2012 to December 2016 period. The static demand scenario was based on the same 2012–2016 data, with a mean for each day being taken across the 5-year dataset; this year of mean values was then applied every year for the future period. The decreased demand scenario used the same starting base as the static scenario, with demand decreasing linearly by 20 % across the period. This decrease is

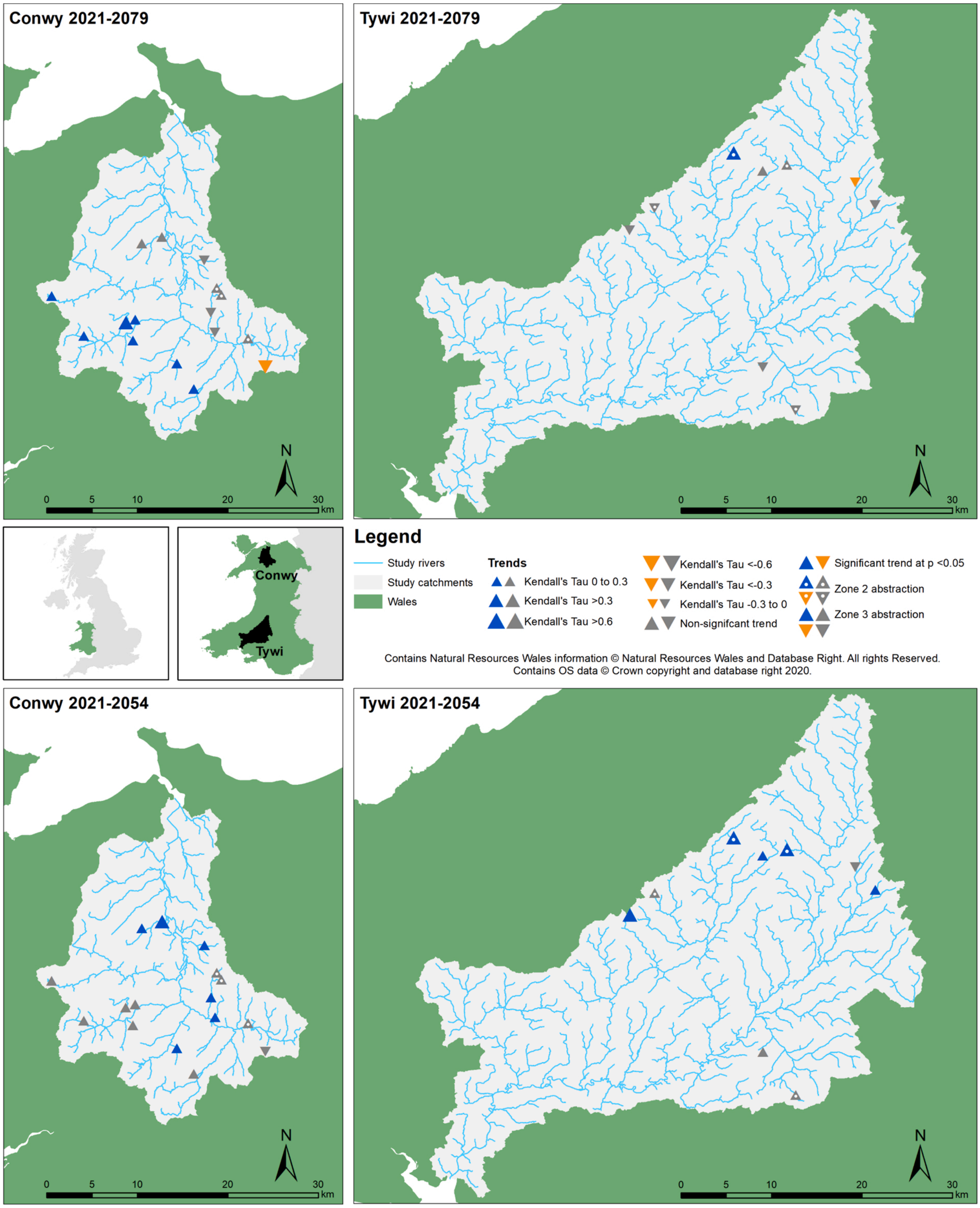

Fig. 7. Overview of the direction, magnitude and significance of annual trends in number of days A_{max} reached for the periods 2021-2079 (top) and 2021-2054 (bottom). Trends detected by Mann-Kendall trend analysis for individual hydroelectric power abstraction locations.

in line with that projected in DCWW's latest water resource management plan (DCWW, 2019b), based on an extensive leakage reduction programme and decreasing domestic water usage, despite a projected increase in the population served. A compensatory HoF was also implemented in WEAP, set at 681.91 million litres per day as laid out in the abstraction license for this location (SWWRA,

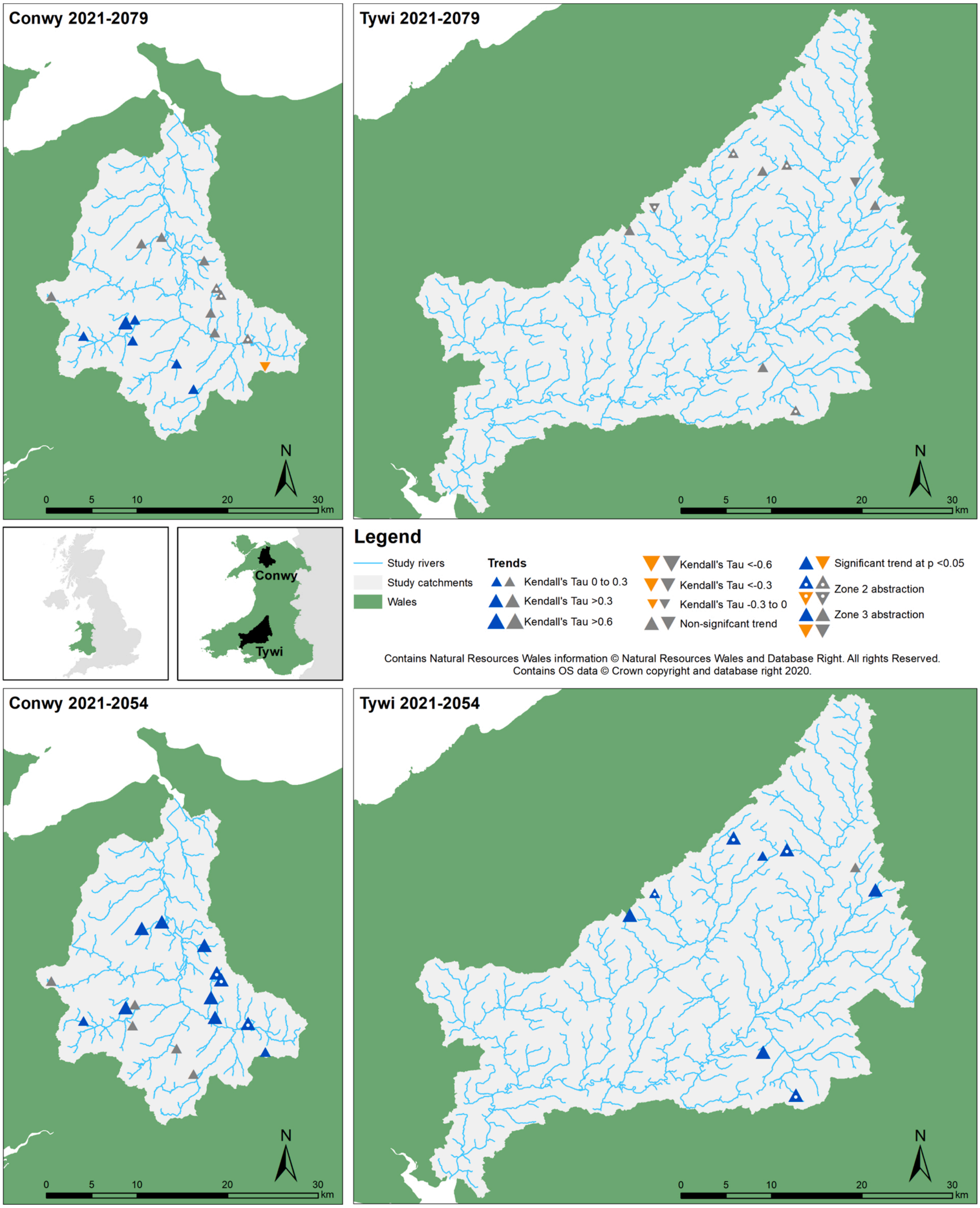

Fig. 8. Overview of the direction, magnitude and significance of annual trends in mean A_{daily} for the periods 2021-2079 (top) and 2021-2054 (bottom). Trends detected by Mann-Kendall trend analysis for individual hydroelectric power abstraction locations.

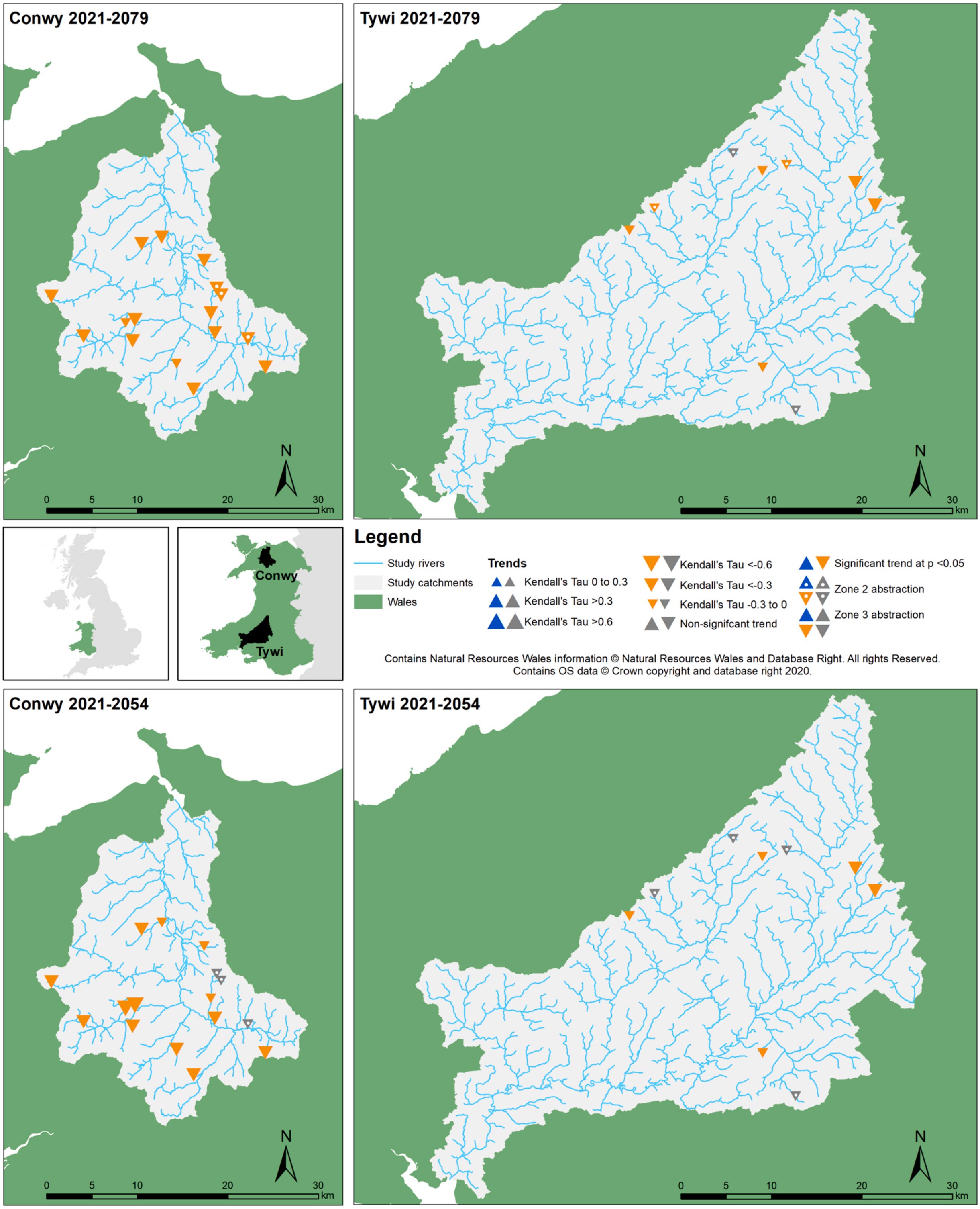

Fig. 9. Overview of the direction, magnitude and significance of annual trends in total abstraction for the periods 2021-2079 (top) and 2021-2054 (bottom). Trends detected by Mann-Kendall trend analysis for individual hydroelectric power abstraction locations.

1965). Total daily unmet demand (D_{unmet}) was then calculated under each scenario using Eq. 3:

$$D_{unmet} = Q - HoF - D \tag{3}$$

where D is daily total water demand; Q and HoF are defined as Eq. 1. Due to the aforementioned system of reservoir low flow support by Llyn Brianne, D_{unmet} is therefore also assumed to be equal to the total daily required reservoir release.

2.5. Trend analysis

Trends in the output data from the HEP and PWS calculations were analysed using the Mann-Kendall (MK) trend analysis (Kendall, 1975; Mann, 1945), in line with other studies that have analysed data relating to hydrological regime change (Dallison et al., 2020; Jin et al., 2020; Mudbhatkal and Amai, 2018; Murphy et al., 2013; Mwangi et al., 2016; Zaman et al., 2016, 2015). The non-parametric test was deemed suitable due to the nature of hydrological data, which is non-normally distributed and exhibits seasonality. The Hamed & Rao method of auto-correlation correction (Hamed and Rao, 1998) was applied, along with Sen's slope estimator (Sen, 1968), to evaluate the direction and size of detected trends. Trends for all factors were analysed based on seasonal (winter, December to February; spring, March to May; summer, June to August; autumn, September to November) and annual averages (hydrological years), or totals, dependent on the factor. HEP trends for each catchment were analysed separately for the average of all Z2 and all Z3 abstractions. The factors analysed were: (1) number of days where A_{daily} is greater than A_{start}, i.e. number of days generation is possible, (2) number of days A_{max} reached, (3) mean A_{daily} on days generation possible, and (4) total seasonal/annual abstraction. For PWS, total unmet demand, number of days demand unmet, and mean unmet demand, were all analysed under each demand scenario. For both HEP and PWS, the mean of the output of all twelve downscaled regional climate model ensemble members was used and is presented in the Results section. The mean of the twelve model runs has been used so as to take account of uncertainty in the future climate projections, and therefore the generated streamflow data. In addition, the MK analysis was applied to the full 2021–2079 (long-term) period, as well as to the end of a medium-term period, 2021–2054. This approach is useful for HEP, as the near future analysis is more in line with the life span of recently installed, and soon to be installed small-scale systems (Hatata et al., 2019; Killingtveit, 2019). For PWS, the near future analysis is a similar period as is currently being planned for, 2050 being the end of the planning period for recently published water resource management plans (e.g. DCWW, 2019b). For Wales specifically, DCWW also recently published a vision document to 2050 (DCWW, 2018). HEP and PWS baseline (2021−2030), near future (2045−2054) and far future (2070−2079) decadal averages were also taken seasonally and annually for the same factors as the MK analysis, to enable further visualisation of a potential medium- and long-term planning needs for both industries.

3. Results

3.1. Hydroelectric power

With regards to change in the number of days annually when A_{start} is achievable, all abstraction locations display a decrease in both the medium-term (2021–2054) and long-term (2021–2079), although these trends are statistically significant for more HEP abstractions in the medium-term analysis than in the long-term (Fig. 6). Trends in the number of days when A_{max} is reached are more variable, especially in the long-term, with differences seen both within and between the two catchments. The Conwy in this period, for example, exhibits statistically significant increases for all abstractions in the west of the catchment, while those on the eastern side vary, with a statistically significant decrease being present for one location (Fig. 7). In the medium-term, there is more agreement

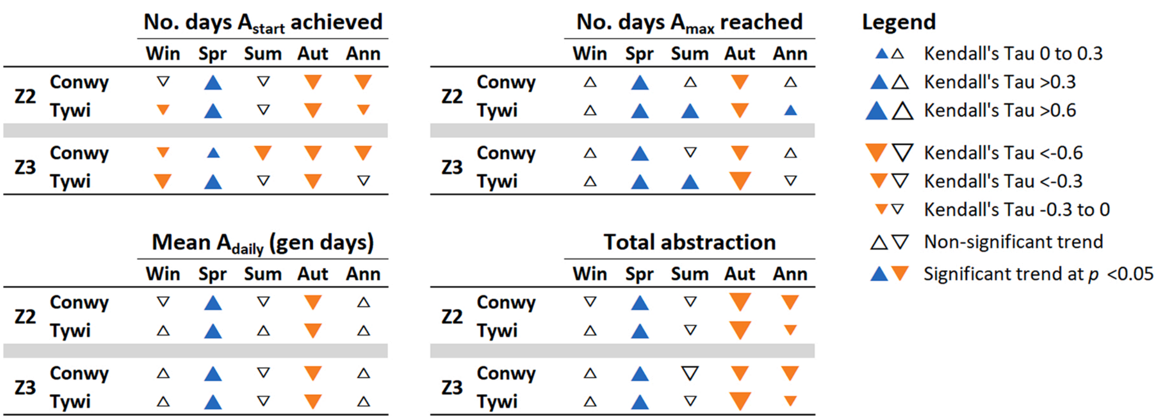

Fig. 10. Overview of the direction, magnitude and significance of annual and seasonal trends in future hydroelectric power characteristics for the period 2021-2079, as detected by Mann-Kendall trend analysis. Based on the average of all Zone 2 (Z2) and Zone 3 (Z3) abstractions in each catchment with the exception of total abstraction, which is based on the sum of the total abstraction of all abstraction locations in each respective zone.

between abstraction locations, with all but one Z3 abstraction in each catchment seeing an increase in the number of days when maximum abstraction is achieved. The combination of these two broad trends (fewer days of abstraction, but larger abstraction volumes available) causes mean A_{daily} on days when abstraction is possible, to increase for the vast majority of locations in both time periods, but especially so in the medium-term (Fig. 8). However, when observing the change in total volume abstracted per year, a decrease is displayed in all locations, for both time periods (Fig. 9). Notably in the medium-term trends for total abstraction, all Z3 abstractions had statistically significant ($p < 0.05$) decreases in volume, while all Z2 locations decline without statistical significance (Fig. 9), the only factor which showed such a split.

Figs. 10 and 11 provide more details on the seasonal trends observed in the four factors studied, for long-term and medium-term respectively. Examining the trends taking place in the 2021–2079 period, it can be seen that the most significant change generally occurs in the spring and autumn, with small declines in annual total abstraction and number of days A_{start} is achieved. In the medium-term, a greater number of statistically significant trends are seen in winter and summer, with increases in annual mean A_{daily} also being statistically significant. Total abstraction also varies considerably between the two periods, with significant increases seen across both catchments and abstraction zones in winter and spring, and decreases in summer and autumn, leading to an overall decrease annually at the Z3 abstractions in the medium-term analysis. Little difference can be seen between the corresponding trends for the two catchments, with trend direction agreeing in all but three occasions, and few occasions of varying magnitude of change. In terms of difference between the two abstraction types, once again little variation is seen. However, when studying the percentage change from the baseline (2021−2030) annual average, with the near and far future decadal annual averages (Table 4), large differences in the number of days A_{max} is reached are shown between the zones. In the far-future average, the Z3 abstractions display a 9 % decline in Tywi and stay stable in Conwy. Nonetheless, the Z2 abstractions increase quite significantly in both catchments, 32 % and 18 % respectively. Few differences are seen between the zones, catchments or time periods for the other factors studied. Finally, with the exception of total abstraction, the magnitude of change from the baseline is greater for the near future than far future.

3.2. Public water supply

Under all three demand scenarios, in both the medium- and long-term, we observe an increase in the number of days annually when streamflow is not sufficient to satisfy demand, as well as an increase in the mean and total unmet demand volume (Fig. 12). These trends are larger in magnitude for the 2021–2054 period and are also statistically significant for this period ($p < 0.05$), with the exception of mean unmet demand in the decreased demand scenario (Fig. 12). No unmet demand is recorded at any point in the winter months under any scenarios, whereas Kendall's Tau results suggest a decrease in unmet demand in spring, especially in the medium-term analysis, although this is not statistically significant. Autumn displays the most consistency in trends across both time periods and the three demand scenarios, with large magnitudes of change seen in total unmet demand and number of days demand unmet.

Further analysis (Table 5) reveals that for all factors considered, and under all demand scenarios, the degree of change between the annual averages of the baseline and near future, is much greater than that between the baseline and far future. For example, under the increased demand scenario, total unmet demand is 167 % higher than the baseline in the near future, whereas the far future period is only 84 % higher. Similarly, for the number of days demand is not met in the static demand scenario, the near future average is 151 % higher than the baseline at 42.4 days per year, compared to only 30.7 day per year in the far future period, a 77 % increase on the baseline of 17.2 days (Table 5). The same is true for mean unmet demand in the decreased demand scenario, with the near future period being 49 % higher than the baseline, and the far future being only 10 % greater.

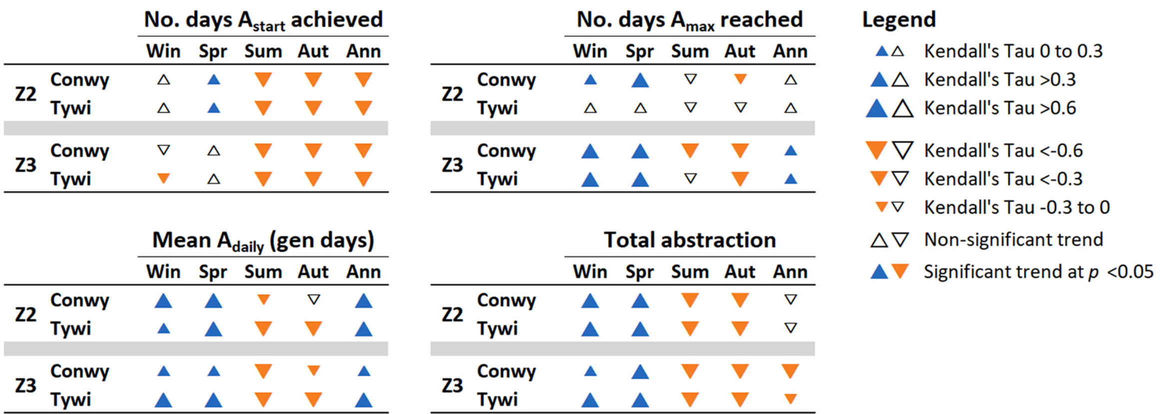

Fig. 11. Overview of the direction, magnitude and significance of annual and seasonal trends in future hydroelectric power characteristics for the period 2021-2054, as detected by Mann-Kendall trend analysis. Based on the average of all Zone 2 (Z2) and Zone 3 (Z3) abstractions in each catchment with the exception of total abstraction, which is based on the sum of the total abstraction of all abstraction locations in each respective zone.

Table 4
Percentage change in annual hydroelectric power characteristics when comparing far (2070-2079) and near (2045-2054) decadal averages with a baseline decade of 2021-2030.

			A_{start} achieved	A_{max} reached	Mean A_{daily}	Total abstraction
Z2	Conwy	2070–2079 average	−13 %	+18 %	+1 %	−11 %
		2045–2054 average	−15 %	+54 %	+12 %	−5 %
	Tywi	2070–2079 average	−9 %	+32 %	+1 %	−7 %
		2045–2054 average	−11 %	+47 %	+8 %	−2 %
Z3	Conwy	2070–2079 average	−11 %	0 %	+3 %	−9 %
		2045–2054 average	−12 %	+11 %	+ 5 %	−8 %
	Tywi	2070–2079 average	−7 %	−9 %	−1 %	−8 %
		2045–2054 average	−13 %	+11 %	+5 %	−7 %

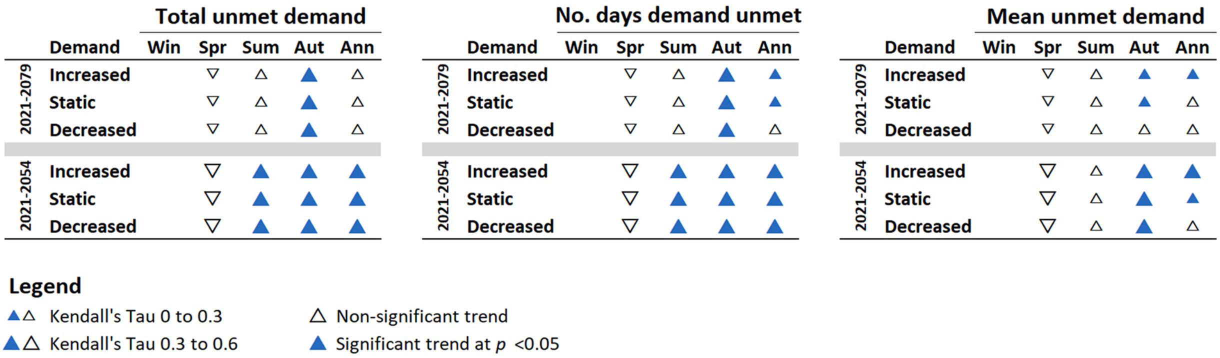

Fig. 12. Overview of the direction, magnitude and significance of annual and seasonal trends in future public water supply unmet demand characteristics for the periods 2021-2079 and 2021-2054, as detected by Mann-Kendall trend analysis. No unmet demand is recorded in winter throughout the future period; therefore, no trends are displayed.

Table 5
Percentage change in annual public water supply unmet demand characteristics when comparing near (2045-2054) and far (2070-2079) future decadal averages with a baseline decade of 2021-2030.

		Increase demand		Static demand		Decreased demand	
		Value	% change from baseline	Value	% change from baseline	Value	% change from baseline
Total unmet demand (million m^3)	2021–2030	1.55		1.53		1.51	
	2045–2054	4.12	+167 %	3.95	+159 %	3.60	+138 %
	2070–2079	2.84	+84 %	2.58	+69 %	2.11	+40 %
Days demand unmet	2021–2030	17.2		17.2		17.2	
	2045–2054	43.9	+155 %	43.4	+151 %	42.8	+149 %
	2070–2079	31.4	+83 %	30.7	+77 %	28.6	+66 %
Mean unmet demand (m^3)	2021–2030	57,015		55,893		55,639	
	2045–2054	93,162	+63 %	90,232	+61 %	83,140	+49 %
	2070–2079	73,506	+29 %	68,721	+23 %	61,351	+10 %

4. Discussion

4.1. Hydroelectric power

The results of the MK trend analysis conducted on HEP abstraction characteristics display a range of changes, with most variation seen between the seasons and time periods studied, rather than between catchments or abstraction zones. These patterns are driven by the streamflow changes shown in Fig. 3. An example of this are the declines seen in spring and summer flows in Conwy and Tywi up to the late 2050s, followed by an increase in summer flows to the end of the study period for Tywi and a plateau for Conwy. Autumn flows plateau after this point for both catchments. These seasonal streamflow changes lead to the differences in trends observed in the MK analysis, with larger and more statistically significant results being seen in the medium-term than long for declines in mean abstraction, number of days A_{start} achieved, and number of days A_{max} reached. Changes in these factors in summer in particular are only significant in the medium-term analysis, due to the levelling off (Conwy) and increase (Tywi) seen in streamflow after this period. This observed shift towards less days and volume of abstraction in the summer and autumn, and an increase in the winter and spring is in line with previously published research for Wales and the UK. To our knowledge, the only previous study that has investigated climate change impacts on hydropower in Wales specifically is the aforementioned work of Carless and Whitehead (2013). Their research presents trends in streamflow and potential HEP output for streams in the upper Severn catchment, similar in nature to the abstraction locations studied in the present research. A baseline, 2020, and 2050 scenarios are considered, with a marked decline in flow and power output in summer and early autumn months displayed in 2050 (Carless and Whitehead, 2013). Winter and early spring months show a smaller magnitude increase for the same period, leading to a stable situation annually (Carless and Whitehead, 2013). These results align well with that of our study's medium-term trend analysis for total abstraction. While no further studies use Wales as a region of focus specifically, other research based on the UK, or regions thereof, seems to be consistent with our results; Scotland for example, which is comparable to Wales due to the similar nature of catchments and also due to the high uptake of HEP in the country. Sample et al. (2015) summarises the research on the potential impacts of climate change on Scotland's HEP. It is suggested that run-off, which is highly sensitive to climate change, is closely linked to generation potential. This relationship, in line with the results of this study, is projected to cause a decline in summer generation potential; although this is likely to be offset in the winter, HEP schemes may be unable to make use of the higher flows due to design limitations (Sample et al., 2015). Further work in Scotland by Thompson (2012) on the impacts of climate change on streamflow also lend weight to the findings of this research, once again suggesting an accentuation of low summer flows and high winter flows in the future. These trends are also echoed on a UK scale by research such as UK CEH (2012) and Kay et al. (2020) both corroborating the seasonal and annual driving streamflow trends observed in the study catchments of this research.

Furthermore, the trends observed of mean abstraction volume increasing, while total abstraction volume is decreasing, suggests that there will be fewer days of abstraction in the future, but with greater abstraction per day. This trend also fits with the observed decrease in the number of days A_{start} is reached, and the increases seen in the number of days A_{max} is achieved. Once again, this is particularly pronounced in the medium-term analysis and is supported by research on low and high flows in Wales. Collet et al. (2018); Marx et al. (2018); Thober et al. (2018) and Visser-Quinn et al. (2019) all suggest that for Wales, in the future, the magnitude, duration and frequency of extreme high and low streamflows will increase.

In terms of observed differences between Z2 and Z3 abstraction types, a smaller magnitude of decline is observed for change in total abstraction in Z2 abstractions compared to Z3 in the medium- and long-term, as well as lack of statistical significance. This suggests that Z2 abstractions are potentially more resilient to climate-induced streamflow change in terms of annual total generation potential. This is possibly caused by the greater volume of water that it is allowable to abstract at these locations, being 1.3 times Q_{mean}, as opposed to Q_{mean} only in Z3 abstractions. This difference allows for Z2 abstractions to make greater use of larger magnitude flows and the observed increases in number of days A_{max} is reached annually. This is further exemplified in the fact that Z2 abstractions on average in both the medium- and long-term have a larger increase in the number of days A_{max} is reached, than Z3 abstractions.

While differences are seen for certain aspects between the two abstraction conditions zone types, little difference in observed trends is seen when comparing the two catchments. This lack of variation is likely due to the fact that the vast majority of the currently operating schemes, and therefore those studied, are located in the uppermost reaches of the catchments, predominantly on first order streams. This positioning leaves little time for LULC differences to cause impact to run-off generation and streamflow significantly between catchments. The same is true for topographical characteristics, with the majority of abstractions being located in topographically homogenous areas across the two catchments. While all four of the factors studied are important for HEP scheme design, perhaps the most important in terms of future profitability is total abstraction. For all time periods, catchments and abstraction zones, a decline is observed, suggesting less generation output in the future.

4.2. Public water supply

When viewing the unmet demand trend analysis results with the streamflow and demand trends, it can be seen that streamflow is the major factor, rather than water demand. In particular, large declines observed in summer and autumn streamflow lead to continued shortages of water, even in the reduced demand scenario. Similarly to HEP, the characteristics of future streamflow change also correspond with the difference seen between the medium and long-term trend analysis conducted for PWS unmet demand. Spring streamflows increase considerably from the mid-2040s, while winter flows display a small increase; annual streamflow volume remains relatively stable throughout. Increases in winter and spring streamflows however do not factor into annual mean and total unmet demand, as streamflow is continually sufficient during these seasons. This means there is no offset for the increased demand and decreased streamflow seen in summer and autumn, leading to an increase annually in the number of days and volume of unmet demand under all scenarios. This problem is particularly pronounced in the medium-term, with both summer and autumn streamflow declining most steeply up to the mid-2050s. These results agree with published literature, with studies such as Sanderson et al. (2012); Henriques et al. (2015), and Afzal and Ragab (2019) projecting large decrease in water availability by the 2050s and beyond for the UK, and Wales specifically. Furthermore, the findings are commensurate with reports from organisation such as the ASC (2016a,), stating more action is needed to tackle future water supply security; Welsh Government (2015), detailing the necessary steps for resilience in Welsh water supply; and, for catchments reliant on river-based abstraction such as Tywyn Aberdyfi and Pembrokeshire, DCWW (2019b). Imbalances observed could lead to problems for water supply, especially in times of prolonged drought, as increases in winter and spring flow will do little to combat summer and autumn shortages if reservoirs are already full.

4.3. Study implications

With regards to HEP abstractions, due to lack of scheme specific data, the results represent an indication of future change in generation potential and timing for the study catchments, and more broadly for catchments across Wales, and the 364 HEP projects there within (Welsh Government, 2019). For example, seasonal shifts in streamflow, and therefore generation capacity will likely still impact on specific scheme layouts in a similar way to that that has been assumed in this study. The results are therefore helpful in planning future schemes and more generally, alteration in UK energy mix. Significantly less generation is expected to be possible in the summer and autumn in the future, which will be important to consider when planning the future resilience of the energy network. Overall, the results show that in the medium-term (2021–2054), abstraction characteristics and potential at installed HEP generation sites is likely to change greatly compared to the baseline; this is significant as this period falls at the end of the general lifespan of small hydroelectric projects (~40 years) built in the last and upcoming five years (Hatata et al., 2019; Killingtveit, 2019). For those sites under development in the next five years, it may be beneficial to review scheme design in view of future flow conditions, for example by installing a larger turbine to make more use of increase in high flows, thus maximising generation potential over the lifetime of the project. In the longer-term, the magnitude of observed changes is smaller for all factors except total abstraction, than the medium-term. Therefore, when site redevelopment and replacement opportunities arise in the future, it will be important to once again looking at future projected change to best determine the most efficient scheme upgrades and alterations.

In terms of PWS, while the specific abstraction studied may be relatively resilient to future changes in streamflow, due to the supporting flow provided by the large upstream reservoir, the results of this work could have important implications for other, non-supported, direct river abstractions. The changes in streamflow and results on unmet demand demonstrated in this study, if applied to other catchments in Wales and the UK, could have major implications for future water supply sustainability. The increases in unmet demand that have been observed, even under a decreased demand scenario, clearly suggests that the pace of change in reduction of water demand by processes such as leakage reduction and domestic water use education and awareness raising, needs to be implemented as soon as possible. These measures should certainly be the first step in ensuring future water supply security, rather than large infrastructure projects to increase supply, in all but the most pressing of cases.

The results and implications of this work can also be paralleled to other large water abstractors in the region which will be operating under the same streamflow regime changes. Industrial and agricultural users in particular could face challenges, causing alterations in operation practices and timing, due to lack of available water, especially for those abstracting directly from rivers and streams. The abstraction location and use data used to identify run-of-river HEP schemes for this study details over 217 surface water-based abstractions used for industrial and commercial purposes, and a further 444 used for agriculture across Wales. These numbers highlight the potential scale of impact of future hydrological regime changes, and the need to act now to ensure resilience to such changes.

5. Conclusions

This research has demonstrated clear trends in future availability of water for the HEP locations studied in the Conwy and Tywi catchments, as well as the major PWS abstraction in the Tywi. Our results highlight that spring and autumn are the seasons most affected long-term by water availability, while winter and summer are more impacted in the medium-term. The results also demonstrate the need for action now, especially in terms of the planning and design of HEP installations. Schemes and turbines must be designed with future streamflow patterns in mind, in particular increasing winter and spring flows, rather than decreasing summer and autumn flows, thus allowing for the maximisation of power generation over the course of a year. Additionally, regardless of future demand decline, increased pressure is likely to be placed on PWS due to large declines seen in future streamflows, therefore careful planning is also required here in order to ensure continued water supply.

Finally, we suggest avenues of future research. Firstly, the impact of different climate change/emissions scenarios on future HEP output and PWS availability is required at a national scale. While a worst-case scenario approach has been taken in this study, it is paramount to consider the range of potential outcomes under different emissions pathways, to ensure that the most proportionate future planning and adaptation measure are undertaken. Furthermore, research on specific HEP schemes, with historical generation data, would be highly beneficial as this would allow future climate change scenarios to be tested after calibration with actual data, giving a better understanding of how future hydrological regime change will impact on generation potential. Secondly, further research taking a holistic view of all catchment abstractions is needed, including industrial, commercial and agricultural purposes as well as PWS and HEP. This approach would give greater insight to how total catchment water demand will impact on individual water users, as well as the catchment as a whole. In addition to this, the inclusion of impacts of other climate change mitigation measures, such as upland management for flood control, would give a complete picture of future potential alterations. This holistic catchment level approach would give the best chance of ensuring fair and equitable distribution of changing future water resources.

CRediT authorship contribution statement

Richard J.H. Dallison: Conceptualization, Methodology, Software, Formal analysis, Investigation, Data curation, Writing - original draft, Writing - review & editing, Visualization. **Sopan D. Patil:** Conceptualization, Software, Writing - review & editing, Supervision. **A. Prysor Williams:** Writing - review & editing, Supervision.

Declaration of Competing Interest

The authors report no declarations of interest.

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